TanDEM-X Scientific Results and Future Formation Flying SAR Missions

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Abstract: TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurements) is an innovative spaceborne radar interferometer mission that was launched on June 21, 2010. This paper gives an overview of scientific experiments that have been conducted during the TanDEM-X commissioning phase. Further, an outlook is given on future formation flying interferometric SAR missions.

1 Introduction

The primary objective of the TanDEM-X mission is the generation of a world-wide, consistent, timely, and high precision digital elevation model (DEM) aligned with the HRTI-3 specification as the basis for a wide range of scientific research, as well as for commercial DEM production [1]. This goal is achieved by extending the TerraSAR-X mission by a second, TerraSAR-X like satellite (TDX) flying in close formation with TerraSAR-X (TSX). Both satellites form together a large single-pass SAR interferometer with the opportunity for flexible baseline selection. This enables the acquisition of highly accurate cross-track and along-track interferograms without the inherent accuracy limitations imposed by repeat-pass interferometry due to temporal decorrelation and atmospheric disturbances. Besides the primary goal of the mission, several secondary mission objectives based on along-track interferometry as well as new techniques with bistatic SAR have been defined, representing an important and innovative asset of the TanDEM-X mission. TanDEM-X is implemented in the framework of a public-private partnership between the German Aerospace Center (DLR) and EADS Astrium GmbH. The TanDEM-X satellite was successfully launched on June 21, 2010.

2 TanDEM-X Experiments

TanDEM-X provides the remote sensing scientific community with a unique data set to demonstrate new bistatic and multistatic radar techniques for enhanced bio- and geophysical parameter retrieval. The following subsections summarize some of the advanced capabilities of TanDEM-X which can be operated in a multitude of modes and configurations [1]. First exciting results, which were obtained during the TanDEM-X commissioning phase, already demonstrate the great potential of bi- and multistatic SAR to serve novel and extremely powerful remote sensing applications. The intention of this paper is to provide only a succinct overview of the wide range of possible applications. A complete description of the experiments and a detailed discussion of their results can be found in the provided references. Many of the experiments form the basis for future formation flying SAR missions.

2.1 Velocity Measurements from Space

TanDEM-X has the capability to provide highly accurate velocity measurements of moving objects within a large coverage area. This can be achieved by comparing the amplitude and phase of two SAR images acquired at slightly different times (Figure 1). By adjusting the along-track displacement between the TDX and TSX satellites from almost zero to several tens of kilometers, TanDEM-X can adapt its sensitivity to a broad spectrum of velocities ranging from less than a millimeter per second to more than hundred kilometers per hour. The Helix satellite formation employed by TanDEM-X enables even a minimization of the effective across-track baseline for a given latitude and incident angle, thereby reducing the complexity in the velocity estimation process. Along-track interferometry can furthermore be enhanced by the so-called dual-receive antenna mode in each of the two tandem satellites, which provides additional phase centers separated by a short along-track baseline of 2.4 m. The combination of short and long baseline SAR data acquisitions improves both the detection and localization of moving objects and resolves phase ambiguities in case of fast scatterers. TanDEM-X provides hence a unique SAR system with four phase centers separated in the along-track direction. Potential applications are Ground Moving Target Indication (GMTI), the measurement of ocean currents, as well as the monitoring of sea ice drift and rotation.

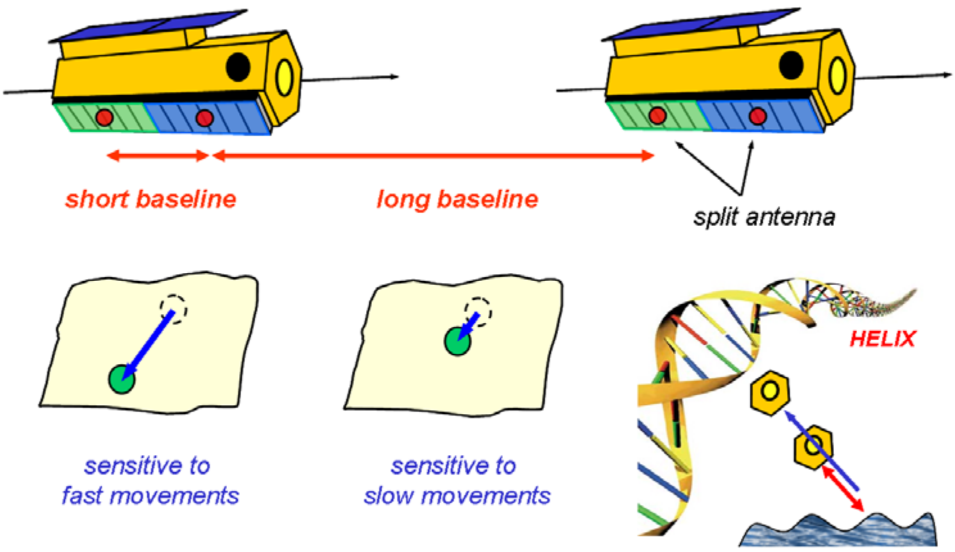

Figure 1: Velocity measurements with TanDEM-X. The Helix satellite formation allows a flexible adjustment of the desired along-track separation between the satellites. In addition, a short along-track baseline is provided by each satellite.

Figure 2 shows as a first example the observation of ship movements in the Strait of Gibraltar [3]. The data were acquired during the monostatic commissioning phase where the satellites had an along-track separation of 20 km [2]. This separation corresponds to a time lag of 2.6 seconds. The 2-D velocity vector could be measured with an accuracy of 1km/h by comparing the ship positions in the TSX and TDX SAR images (cf. [3] for details). The velocity measurements have been validated with independent data obtained from the Automatic Identification System (AIS).

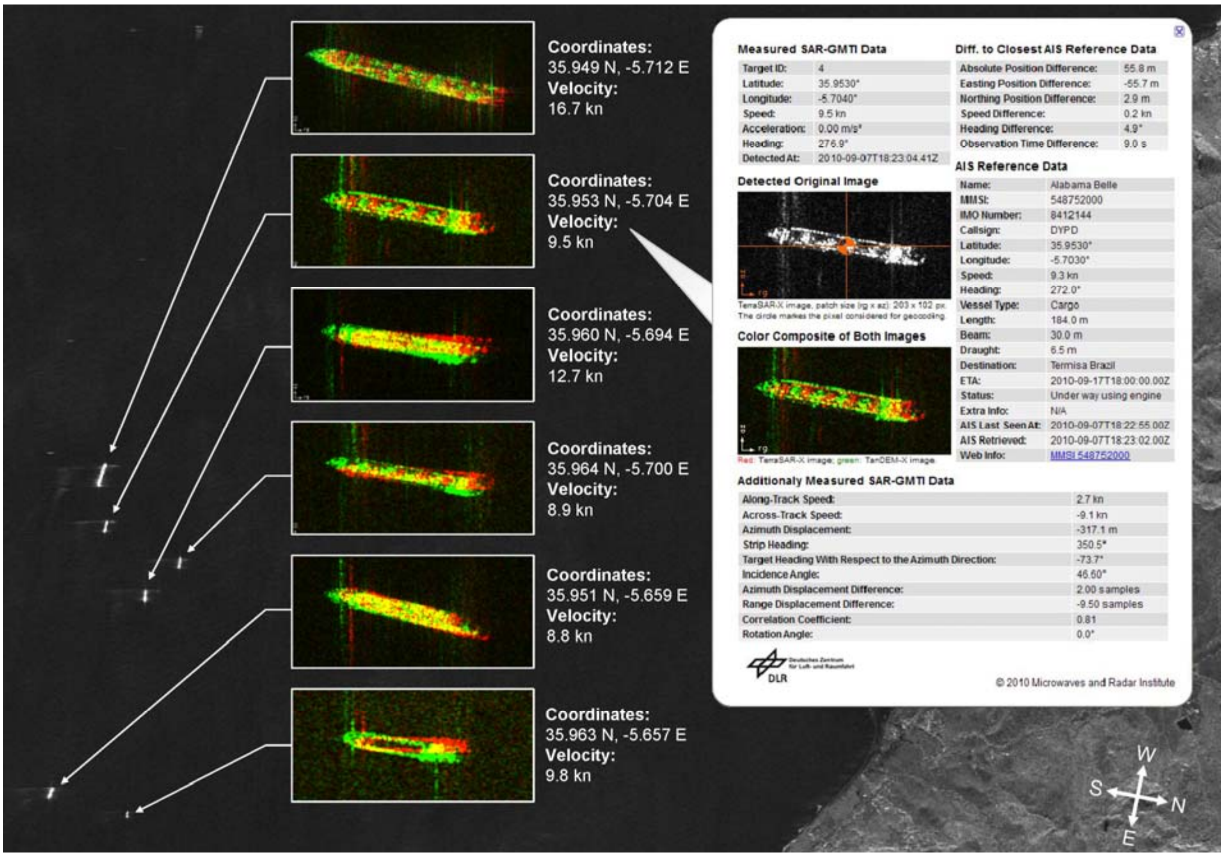

Figure 2: Ship movements observed with TanDEM-X during the monostatic commissioning phase. The ship displacements can be seen from the insets showing TSX and TDX image patches overlaid in different colors. The estimated velocities are in excellent agreement with AIS reference data (right).

2.2 Large Baseline Cross-Track Interferometry

Large baseline interferometry takes advantage of the high RF bandwidth of the TSX and TDX satellites, allowing for coherent data acquisitions with cross-track baselines of up to 5 km and more. Note that less than 5% of the maximum possible (critical) baseline length is used during nominal DEM data acquisition. Large baseline interferograms can hence significantly improve the height accuracy beyond the standard TanDEM-X DEM quality, but the associated low height of ambiguity requires typically a combination of multiple interferograms with different baseline lengths to resolve phase ambiguities, especially in hilly and mountainous terrain. Further opportunities arise from a comparison of multiple large baseline TanDEM-X interferograms acquired during different passes of the satellite formation (Figure 4). This provides a sensitive measure for vertical scene and structure changes. Potential applications are a detection of the grounding line which separates the shelf from the inland ice in polar regions, monitoring of vegetation growth, mapping of atmospheric water vapor with high spatial resolution, measurement of snow accumulation or the detection of anthropogenic changes of the environment, e.g. due to deforestation. Note that most of these combinations rely on a comparison of two or more single-pass (large baseline) cross-track interferograms and do hence not necessarily require coherence between the different passes. Further information can be gained from an evaluation of coherence changes, potentially augmented by polarimetric information. This is for instance well suited to reveal even slight changes in the soil and vegetation structure reflecting vegetation growth and loss, freezing and thawing, fire destruction, human activities, and so on. The combination of repeated TanDEM-X single-pass interferograms enables hence the entry into a new era of interferometric and tomographic 3-D and 4-D SAR imaging as it was ERS-1/2 for the development of classical repeat-pass SAR interferometry.

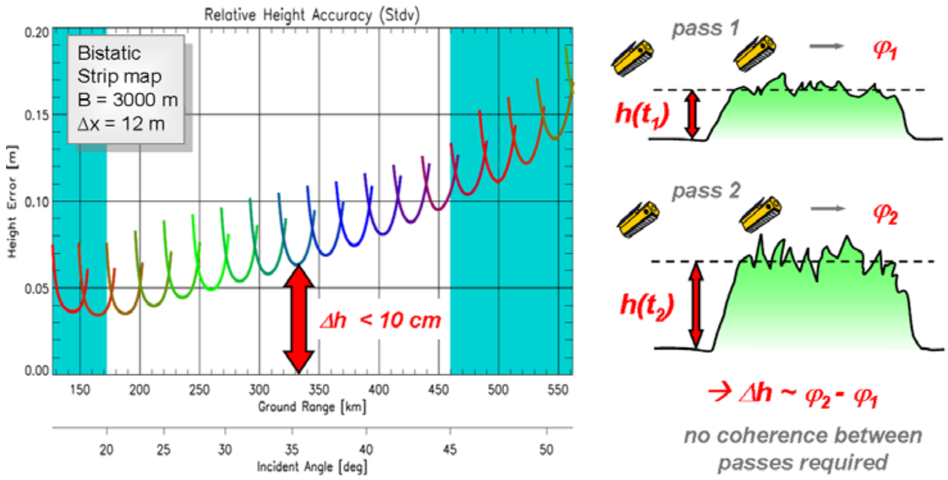

Figure 3: Performance example for large baseline DEM acquisitions with TanDEM-X (cross-track baseline = 3000 m, posting = 12 m). A relative height accuracy (single point standard deviation) better than 10 cm is predicted.

Figure 4 shows as a first example a large baseline DEM which was acquired by TanDEM-X on July 16, 2010 in the Russian Arctic (October Revolution Island) [4]. The DEM was part of a longer data take that used a sophisticated commanding to obtain a large baseline interferogram while TDX was still drifting towards TSX from its initial along-track separation of 15700 km. At the time of data acquisition, the two satellites were 380 km apart from each other, resulting in a temporal separation of 50 seconds. Earth rotation caused a cross-track baseline of 2 km which corresponds to a height of ambiguity of only 3.8 m. A squinted operation was necessary to provide a sufficient overlap of the Doppler spectra. The right hand side of Figure 4 shows the predicted (black curve) and estimated (gray curve) standard deviation of the point-to-point relative height error for a linear slice through the DEM. The predicted error was calculated from the coherence measurements and the estimated error was obtained by high-pass filtering the DEM slice [4]. Both results show that the height accuracy is in the order of 20 cm. This demonstrates the great potential of formation flying SAR missions to obtain high resolution elevation information with decimeter accuracy, thereby enabling new remote sensing applications. An example is the monitoring of height changes over glaciers, ice caps or ice sheets to quantify their ice mass balance and a dedicated formation flying SAR mission has already been proposed for this purpose [5].

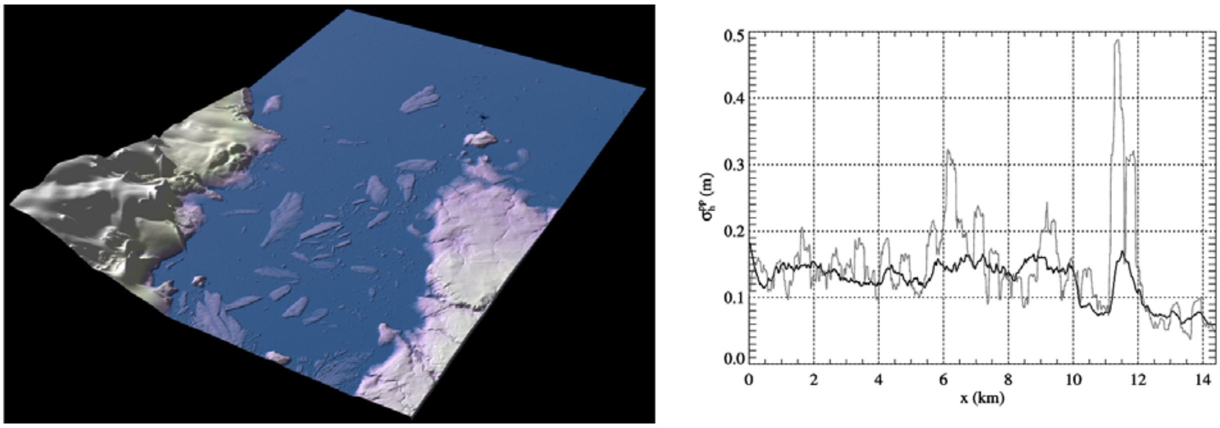

Figure 4: Large baseline TanDEM-X DEM from the border of October Revolution island (left) and predicted (black) vs. estimated (gray) point-to-point height accuracy along a DEM slice (cf. [4] for details).

2.3 Polarimetric SAR Interferometry

Polarimetric SAR interferometry combines interferometric with polarimetric measurements to gain 3-D structure information from semi-transparent volume scatterers in a single pass [6]. A prominent example is the measurement of vegetation height and density which forms also the basis of future formation flying SAR missions dedicated to global environmental monitoring (cf. Section 3). Figure 5 shows as an example the height differences obtained for a dual-polarized TanDEM-X spotlight acquisition of an agricultural field in Russia. The data were acquired during the monostatic commissioning phase with a perpendicular baseline of 275 m, demonstrating the potential of crop height estimation. Future experiments will also employ fully polarimetric acquisitions.

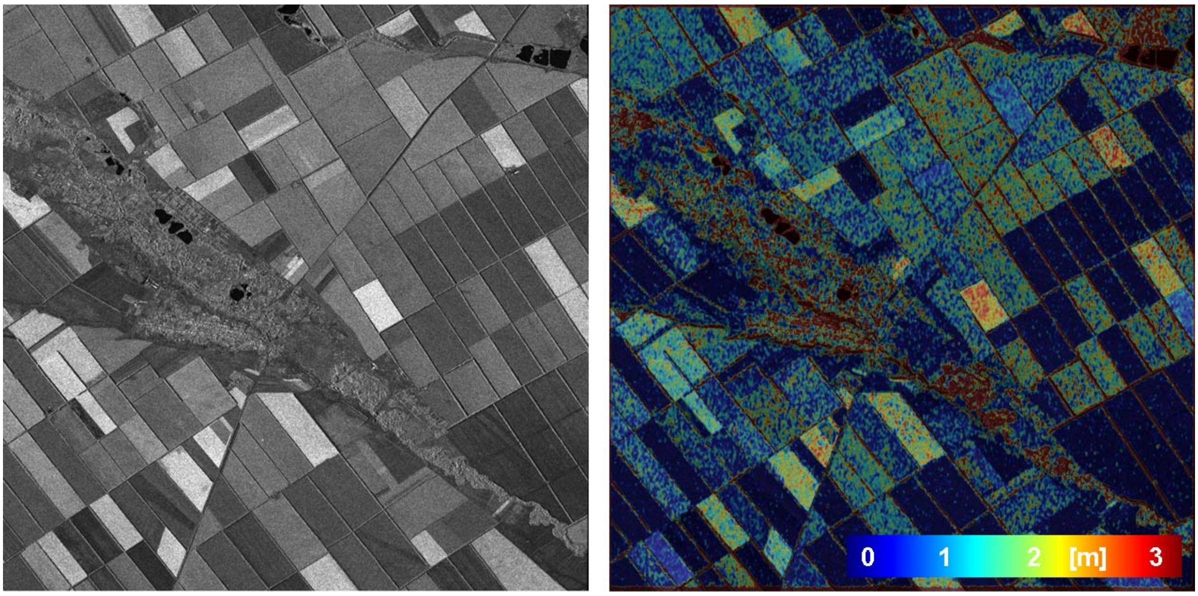

Figure 5: Polarimetric SAR interferometry with TanDEM-X. Left: amplitude of SAR image. Right: interferometric height difference between HH and VV channels.

2.4 Bistatic SAR Imaging

Bistatic SAR imaging provides additional observables for the extraction of important scene and target parameters. TanDEM-X allows for the simultaneous acquisition of bistatic and monostatic images in a single data take to obtain a highly informative set of multi-angle observations. A quantitative evaluation of the bistatic radar cross-section (RCS) and a comparison with its monostatic equivalent facilitates the detection and recognition of targets. The segmentation and classification in radar images is expected to be improved by comparing the spatial statistics of mono- and bistatic scattering coefficients. This is supported by airborne bistatic radar experiments performed by DLR and ONERA, which revealed significant changes of the scattering behaviour for both artificial and natural targets even in case of rather small bistatic angles. A joint evaluation of mono- and bistatic SAR images could also be used to isolate different scattering mechanisms. An example is the distinction between highly directive dihedral returns from more isotropic volume scattering. Bistatic SAR has moreover potential for the retrieval of sea state parameters, the estimation of surface roughness and terrain slope, as well as stereogrammetric, meteorological and atmospheric applications. The bistatic data acquired with TanDEM-X will hence provide a unique data source to improve our understanding of bistatic SAR imaging and its exploitation for future remote sensing applications. A first bistatic data take has been acquired over Brasilia during the monostatic commissioning phase where the satellites were separated by 20 kilometers. Figure 6 shows an overlay of the bistatic SAR image with its monostatic counterpart demonstrating significant scattering differences already for very small bistatic angles [7].

Figure 6: Overlay of monostatic (magenta) and bistatic (green) SAR image.

3 Tandem-L

Tandem-L is a German proposal for an innovative interferometric radar mission to monitor the Earth system and its intricate dynamics. Important mission objectives are global inventories of forest height and above-ground biomass, large-scale measurements of Earth surface deformations due to plate tectonics, erosion and anthropogenic activities, observations of glacier movements and 3-D structure changes in land and sea ice, and the monitoring of ocean surface currents. The Tandem-L mission concept is based on co-flying two fully-polarimetric L-band SAR satellites in a close formation. The synergistic use of two satellites enables highly accurate interferometric measurements to derive contiguous 3-D structure profiles and their spatiotemporal evolution. The advanced imaging capabilities and the systematic data acquisition strategy make Tandem-L a unique observatory to significantly advance our scientific understanding of environmental processes in the bio-, geo-, cryo-, and hydrosphere. A detailed description of the mission and its goals can be found in [8]. The German Tandem-L mission proposal has in its primary science objectives several commonalities with the DESDynI mission suggested by the US National Research Council in its Decadal Survey for Earth Science. DLR and NASA/JPL are currently investigating in the scope of a pre-phase A study the feasibility of a joint mission that meets or even exceeds the science requirements of both proposals and provides at the same time a significant cost reduction for each partner.

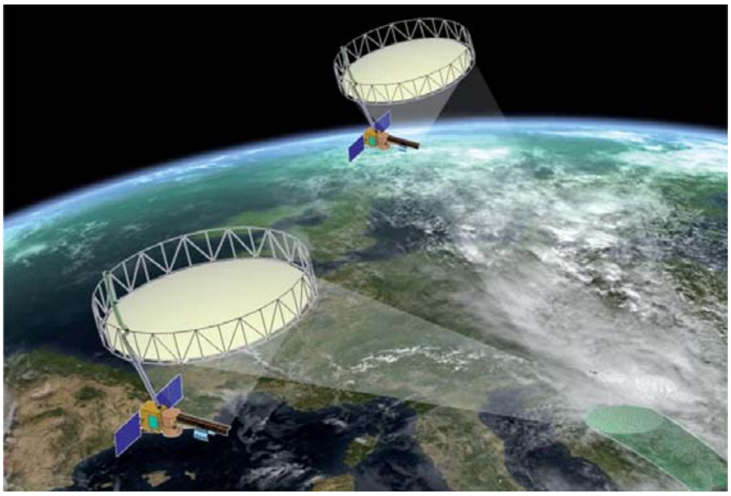

Figure 7: Tandem-L is an innovative SAR mission to monitor dynamic processes on the Earth surface using a pair of L-band satellites flying in close formation.

The Tandem-L mission concept relies on a highly innovative data acquisition strategy using advanced digital beamforming techniques to provide wide swath coverage and short revisit times without sacrificing fine geometric resolution [8]. This innovation enables a frequent monitoring of 2-D and 3-D structure changes with unprecedented spatial and temporal resolution. The systematic acquisition of wide-area single-pass and repeat-pass interferograms with high revisit frequency will open a new era in radar remote sensing and it can be expected that besides the primary mission objectives a wealth of new applications will emerge from the unique Tandem-L observatory.

The Tandem-L satellite system acquires data in two basic measurement modes:

- The ***3-D structure mode*** employs fully-polarimetric single-pass SAR interferometry to acquire structure information and quasi-tomographic images of semi-transparent volume scatterers like vegetation, sand, and ice (cf. Figure 8).
- The ***deformation mode*** employs repeat-pass interferometry in an ultra-wide swath mode to measure small shifts on the Earth surface with millimetric accuracy and short repetition intervals.

The right hand side of Figure 8 shows an example of the predicted accuracy of forest height measurements using the 3-D structure mode. The performance depends on both the forest height and the length of the cross-track baseline (expressed in terms of the vertical wavenumber k_z). Accuracies below 10% can be achieved by combining multiple acquisitions with different vertical wavenumbers.

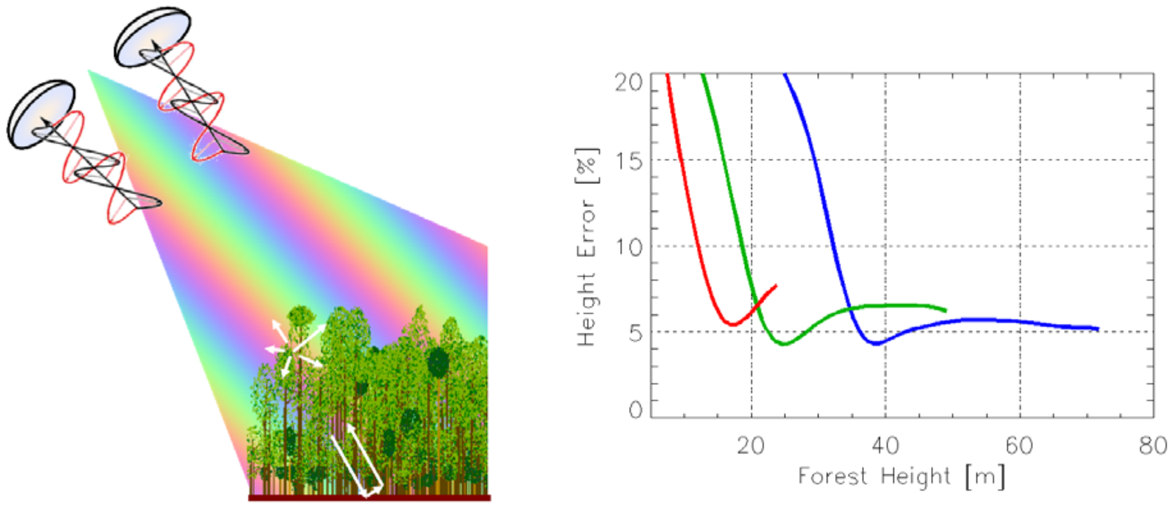

Figure 8: 3-D structure mode (left) and its predicted performance for forest height estimation (right). The colored curves show the expected accuracy of vegetation height measurements for different vertical wavenumbers (blue: $k_z = 0.05$ rad/m, green: $k_z = 0.1$ rad/m, red: $k_z = 0.2$ rad/m, cf. [8] for more details).

The Tandem-L acquisition plan foresees a systematic variation of the cross-track baselines to optimize forest height and vegetation profile measurements in the 3-D structure mode. At least three acquisitions with vertical wavenumbers k_z ranging from 0.05 rad/m to 0.2 rad/m are planned for each season. Fig. 9 shows the correspondence between k_z and the lengths of the perpendicular baselines assuming an interferometric acquisition in bistatic mode. For an orbital altitude of 700 km and incident angles ranging from 30° to 45°, the required perpendicular baselines vary between 750 m and 5 km. This corresponds at the equator to horizontal baselines between 850 m and 6.6 km in case of using a Helix formation with no radial orbit separation at nodal crossing.

A further challenge for Tandem-L is the adjustment of large cross-track baselines at higher latitudes. One opportunity is a large eccentricity offset to provide a sufficient radial orbit separation at high latitudes, but a significant amount of fuel will be required to compensate the resulting motion of libration for longer time periods. Another opportunity is an even larger separation of the ascending nodes, which may then provide sufficient baselines for accurate forest height retrievals in the mid latitudes. Boreal forests at higher latitudes can also be imaged in the alternating bistatic mode [1] which doubles the phase to height scaling, thereby increasing the effective baseline by a factor of two.

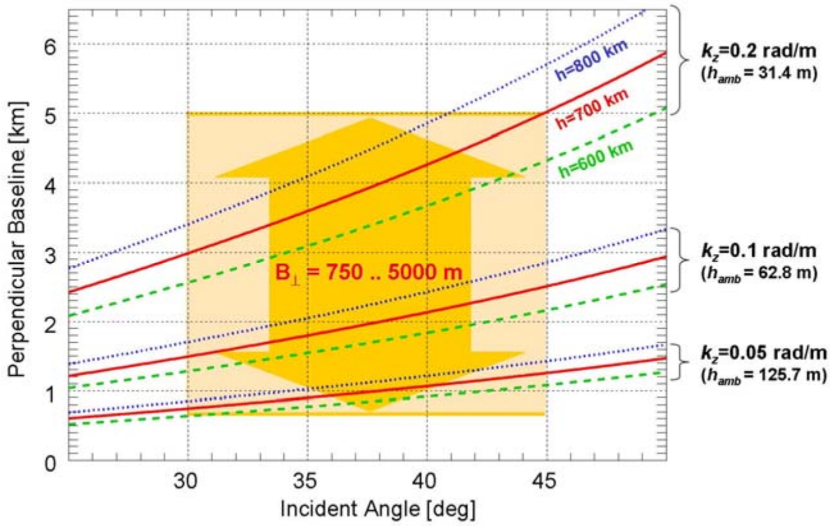

Figure 9: Correspondence between vertical wavenumbers and perpendicular baselines as a function of incident angle and orbit height.

An elegant technique to provide the wide range of cross-track baselines exploits the naturally occurring differential secular variations of the right ascension of the ascending nodes in response to slightly different inclinations. Fig. 9 shows the evolution of the horizontal baselines at the equator for different inclination offsets (expressed as horizontal baselines at orbit turns). An optimized data acquisition concept that provides optimized baselines over the whole mission time is currently under development.

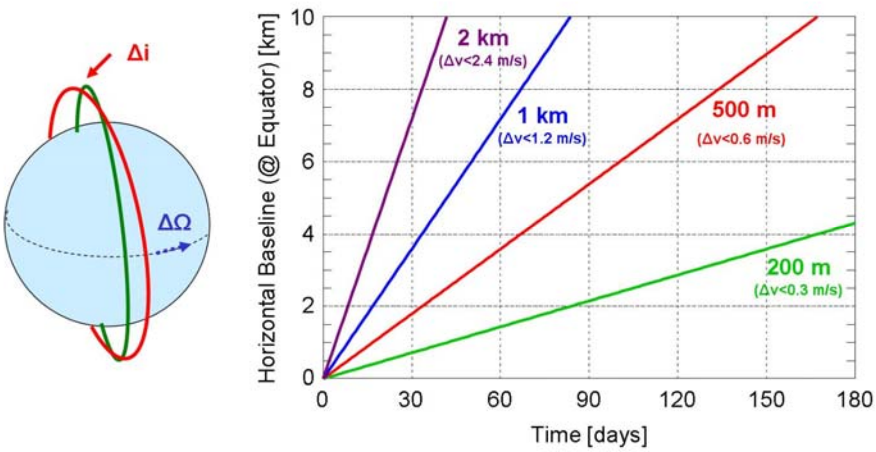

Figure 10: A systematic variation of the cross-track baselines can be achieved by using orbits with slightly different inclinations. The inclination offset causes a relative drift of the ascending nodes, thereby reducing the fuel demands.

4 Conclusions

This paper provides a short overview of the advanced capabilities of formation flying SAR missions to map and monitor the Earth surface and its intricate dynamics. TanDEM-X is the first single-pass multistatic SAR interferometer in space and has the primary objective to acquire a globally consistent and up-to-date DEM with unprecedented accuracy. Beyond its primary mission goal, TanDEM-X is also an ideal testbed to demonstrate a multitude of new bistatic and multistatic SAR techniques and applications. As a further development, the mission proposal Tandem-L builds upon the know-how and experience gathered with TanDEM-X, especially in the areas of close formation flying, system synchronization, systematic data acquisition planning and bistatic SAR processing. Tandem-L relies in addition on highly innovative SAR imaging techniques that have been developed to overcome the limited mapping capabilities of traditional SAR systems. This supports a global data acquisition with short repeat intervals and high spatial resolution, as required for a better understanding of the Earth system and its intricate dynamics. Tandem-L can be regarded as a first step towards a global monitoring system that continuously observes natural and anthropogenic processes which permanently restructure the Earth surface. Further proposals for formation flying SAR missions can be found in [8] and the references therein.

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